Proc 8th Int Coral Reef Sym 2:1995–2000. 1997

ADVANCES IN ENVIRONMENTAL MOORING TECHNOLOGY

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ABSTRACT

The use of environmentally sensitive moorings as a means to reduce or eliminate anchor damage has become a widely accepted tool for managing the coral reef environment. Mooring buoy technology has advanced to adapt to the variety of coral reef habitats found around the world. The original limestone embedment mooring eye technique has been modified to accommodate harder volcanic and granite substrates by using high strength epoxy and smaller drill hole sizes. In soft sand, rubble and grass environments, a deep hydraulically driven anchor rod with a perpendicular resistant plate or helical screw is used to attain sufficient holding power. Large or multiple embedment anchors have been developed with stronger systems to accommodate larger vessels with greater holding power requirements. Extreme tidal ranges, steep slopes, and shallow-sand-covered hard bedrock are challenges for mooring buoy establishment.

INTRODUCTION

Since 1981, embedment anchor technology has evolved to meet the challenges of mooring large vessels in a variety of substrates over a wide geographical range (Table 1). Through advanced technology, mooring buoy deployment has become a significant tool for reducing anchor damage in environmentally sensitive marine habitats and an asset in the management of marine protected areas. The development of several practical embedment anchoring systems has led to advancement in this field. The use of additional hydraulic tools and supporting equipment has also been a factor in the advancement of mooring technology.

The demand for embedment anchors and mooring systems that could be used in a variety of environmentally sensitive substrates has steadily increased. Several adaptations have been developed to meet these needs. When solid limestone substrate is available, coring a hole and cementing a stainless steel eye pin into the bottom continues to be a strong, long-term, cost-effective method of securing a mooring system in a coral reef environment. The single cemented eye pin has been complemented by a heavy-duty inverted "U" anchor for larger vessels and heavier sea conditions. Small diameter drill bits and stainless steel threaded eye pins secured with underwater adhesive epoxy can be effectively used in volcanic areas with extremely hard substrates. The quickly installed small diameter epoxy system is also effective for deep water applications where bottom time is limited.

In unconsolidated substrates such as sand, grass, and loose rubble environments, a Manta Ray™ anchor, driven in with jack-hammer and load-locked, is a strong, cost-effective method of securing mooring systems. For heavier duty applications, multiple Manta Ray™ anchors and deep penetrating helical anchors can provide additional holding power. Most embedment anchoring systems can be installed with portable diver-operated hydraulic tools from a small boat. Hard substrate penetrating helical anchors require greater hydraulic power from a stationary vessel. Embedment anchor systems complement one another, providing security in both hard and soft substrates. They offer a point of attachment for buoy systems that utilize minimal hardware and eliminate the need for heavy chain or cable. These systems can be used with floating line and minimal scope in close proximity to delicate bottom features without sacrificing holding power or causing damage to the surrounding habitat. The use of embedment anchoring systems has also become the preferred mooring technique for demarcation buoys, channel markers, and for securing scientific instruments underwater.

MATERIALS AND METHODS

Hard bottom: Single eye pin mooring anchors
Most of the modifications made to the original system have resulted in increased strength and durability of the system, a wider range of substrate use, and a savings in installation time or cost. In the Florida Keys, the original 10.16 cm (4 in.) diameter eye pin hole was reduced to 5.08 cm (2 in.) and the moulding plaster catalyst initially used for making "quick setting cement" was found to be unnecessary when contained within the drilled core hole. Cement setting times are slower than when catalyst is used, but the cement is easier to work with, particularly in deep water applications. The smaller core hole reduces drilling time and requires less cement than the 10.16 cm (4 in.) hole without sacrificing any holding power. A 5.08 cm (2 in.) core barrel is also less expensive and easier to handle than the larger core barrel. The eye pin is made from 316 stainless steel, 45.72 cm (18 in.) long by 1.59 cm (5/8 in.) diameter with a reduced 4.76 cm (1-7/8 in.) welded cross-rod at the bottom, embedded in Portland Type II cement (Fig. 1).

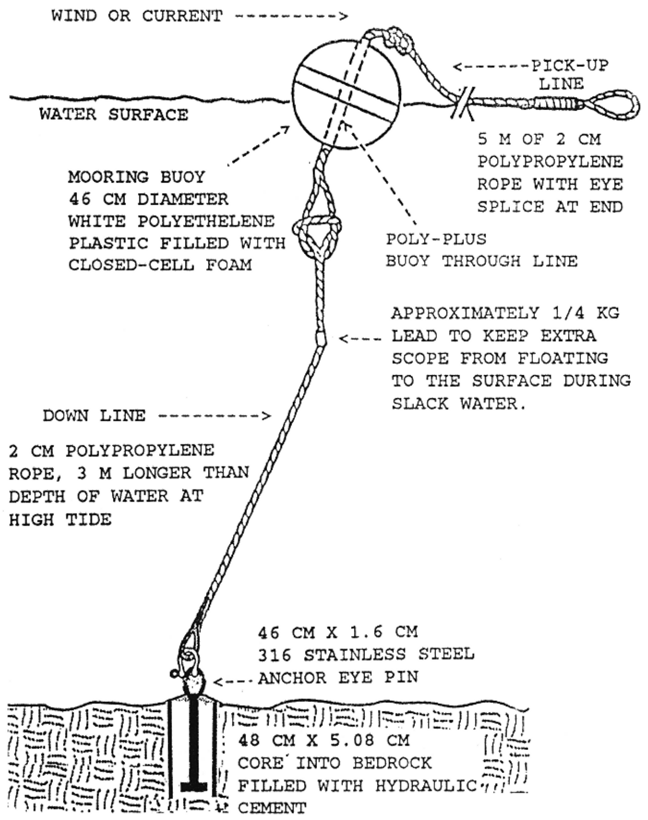

Fig. 1: The Halas Mooring System (Drawing not to scale.)

Portland Type II cement is recommended by the manufacturer for high sulfate environments and applications in seawater such as boat ramps and sea walls. The more commonly found Portland Type I cement has been used at locations where Type II is unavailable. St. Croix, U.S. Virgin Islands and Belize have both used Type I cement in their installations and have seen no difference. Long term observations of Type I cement (more than 10 yrs.) are not available. In the Hawaiian Islands, a 2.22 cm (7/8 in.) drill bit has been used successfully with

Quickcrete cement and 304 stainless steel 45.72 cm (18 in.) by 1.91 cm (3/4 in.) eye pins (Wilkens and Tabata 1989). These eye pins were manufactured from smooth stock steel and initially scored to give holding power and later "beaded" with welding rod to give increased surface area without losing eye pin diameter (Leicher pers. com.). In the Bahamas, good holding power for a heavy 16.76 m (55 ft.) long displacement hull live-aboard boat has been obtained by increasing the standard Key Largo 316 stainless steel eye pin to 55.88 cm (22 in.) by 1.91 cm (3/4 in.) placed in a 5.08 cm (2 in.) hole with Type II cement (Doyle pers. com.).

In the summer and fall of 1994 in response to encountering a variety of hardbottom substrates and differing conditions for setting mooring eye pins including a need to quickly set strong single eye pins in a small diameter hole, a two part underwater adhesive epoxy was tested. Tests in Key Largo were conducted on wet cap rock and included both epoxy-set and cement-set eye pins. Epoxy-set eye pins were also tested underwater in a nearshore limestone substrate. Although cemented eye pins had been used successfully in Key Largo for 13 years, no official pull-out tests had been conducted. In Hawaii some minimal pull tests were performed when eye pins were initially installed experimentally (Wilkens and Tabata 1989).

The epoxy adhesive has an extremely high shear strength and works best when the drilled hole is 0.32 cm (1/8 in.) over the eye pin diameter (Koltenbeck pers. com.). The eye pin is knurled or threaded to provide a rough surface for epoxy adherence which eliminates the need for the cross-rod used at the bottom of the conventional eye pin. Using a 1.91 cm (3/4 in.) solid bit to drill the hole for the 1.59 cm (5/8 in.) eye pin greatly reduces drilling times and eliminates the need for pipe wrenches and core rod. The surface job of mixing cement and delivering it to the bottom is no longer necessary. The epoxy tube and gun can be carried down with the drill and activated underwater as soon as the hole is completed. Delivery of the epoxy adhesive through the mixing nozzle is a clean process producing no turbidity cloud that may result from cement delivery. The epoxy is completely cured in 24 hours and a strain can be placed on the eye pin at that time in contrast to a cemented eye pin that requires several days of curing time. The system is particularly well suited for extremely hard volcanic or granite substrates where drilling times are not practical with 5.08 cm (2 in.) core barrels or in deep water (>20 m) applications.

For the pull-tests, several welders constructed 1.59 cm (5/8 in.) and 1.91 cm (3/4 in.) 316 stainless steel eye pins. The standard Key Largo 45.72 cm (18 in.) by 1.59 cm (5/8 in.) eye pin was used with a 4.76 cm (1-7/8 in.) cross-rod in a 5.08 cm (2 in.) diameter hole cemented with Portland Type II cement and cured for five days. The same welder's eye pin was used without the cross-rod, knurled and set with epoxy with a one day cure. A different welder constructed a threaded 45.72 cm (18 in.) by 1.59 cm (5/8 in.) eye pin welded in the same fashion as the Key Largo eye pin. Several 45.72 cm (18 in.) by 1.59 cm (5/8 in.) threaded eye pins were constructed with a longer overlapped weld site and 45.72 cm (18 in.) by 1.91 cm (3/4 in.) threaded eye pins were also used in the test. A final test was conducted using an inverted "U" anchor set with cement (Table 2).

Hard bottom: Multiple eye pin / "U" Anchors

As use of the original embedment anchor system spread geographically, a variety of conditions were encountered requiring adaptations to the basic system and installation techniques. Although the original single eye pin system successfully mitigated anchor damage of small to mid-sized vessels (up to 20 m long) in reasonable weather, the growing popularity of live-aboard dive vessels up to 32 m long posed a problem. With their large size and ability to stay on buoys longer in rough weather, a stronger system was needed to alleviate the damage that their large anchors were causing.

Table 1: Locations in mid-1996 where environmental reef moorings or embedded mooring anchors have been installed. Approximate numbers of current moorings are indicated. One star in the last column represents a site visited by John Halas to train personnel and/or install mooring systems. Double stars indicate an additional site visit and additional mooring installations.

REGIONS UTILIZING ENVIRONMENTAL REEF MOORINGS

REGION	INITIAL INSTALLATION DATE	APPROX. NUMBER BY 1996	
U.S.A., South Florida	June, 1981	500	*
Cayman Islands, B.W.I.	Sept., 1986	205	*
Netherlands Antilles, Saba	April, 1987	20	*
U.S.A. Hawaiian Islands	July, 1987	45	*
Malaysia, Peninsular	July, 1988	150	*
Turks and Caicos, B.W.I.	Dec., 1988	35	*
Netherlands Antilles, Saba	March, 1989	7	**
British Virgin Islands,B.W.I.	March, 1989	170	*
Belize, C. A.	May, 1990	52	*
Thailand, Phuket	1989	10	
U.S.A., Texas Flower Gardens	May, 1990	12	*
Samoa, American	June, 1990	6	
U.S.V.I. Nat. Park, St. John	Nov., 1990	40	*
U.S.V.I. St. Croix	Feb., 1991	20	*
St.V.& Grenadines, Mustique	March, 1991	25	*
Jamaica, Negril	Nov., 1991	35	
Jamaica, Montego Bay	Dec., 1991	13	*
Honduras, Bay Islands	1991	10	
Bahamas, Bimini Chain	Jan., 1992	76	*
Bahamas, Lucaya G.B.I.	March, 1992	75	*
Puerto Rico	May, 1992	64	*
Anguilla, B.W.I.	June, 1992	50	*
Micronesia, Palau	Sept., 1992	25	*
Bahamas, San Salvador	Dec., 1992	36	*
Bahamas, Exumas/Land&Sea Park	Feb., 1993	105	*
St.V.& Grenadines,Tobago Cays	March, 1993	50	*
Bahamas, Nassau	June, 1993	25	
Egypt, Hurghada (Red Sea)	July, 1993	48	*
Australia, Whitsunday Is.	August,1993	5	*
Belize, Cay Caulker	Sept., 1993	39	*
Bahamas, Exumas/Land&Sea Park	March, 1994	10	*
Saipan	May, 1994	10	*
U.S.A., Hawaii/Molokini, Maui	May, 1994	6	**
Bahamas, Gingerbreads/Bimini	June, 1994	12	**
Bahamas, Harbour Is/Eleuthera	June, 1994	18	*
Indonesia, Bali Barat Nat.Park	Sept., 1994	8	*
Indonesia, Komodo Nat. Park	Sept., 1994	8	*
St. Lucia, Soufriere/SMMA	Dec., 1994	42	*
Dominican Republic	Jan., 1995	30	*
Bahamas, Abaco/Hog Cay	Feb., 1995	3	*
Bahamas, Abaco/Green Turtle Cay	May, 1995	6	*
U.S.V.I. St.Thomas/Reef Ecol.Fd.	May, 1995	50	*
Indonesia, Komodo Nat. Park	Sept., 1994	8	**
St. Lucia, Soufriere/SMMA	Dec., 1995	11	**
Jordan, Aqaba	Jan., 1996	10	
Papua New Guinea, Walinde Bay	March, 1996	14	*
Micronesia, Yap	March, 1996	16	*
St.V.& Grenadines, Tobago Cays	May, 1996	46	**
U.S.A.,Great Lakes (No.IL Scuba)	May, 1996	3	
Aruba/Watersports Assn.	June, 1996	22	*
Bahamas, Abaco/Marsh Harbour	1996	15	
Micronesia, Kosrae	1996	3	
Egypt, Hurghada/HEPCA-Winrock Proj.	Dec., 1996	30	**
APPROXIMATE TOTAL MOORINGS BY 1996:		2,334	

In mid-1987, Steve Smith in the Cayman Islands, needing to obtain greater holding power from the eye pin system for large live-aboard boats, installed triads consisting of three eye pins placed in a triangle pattern approximately 0.6 m apart joined together by chain terminating just off the bottom with a pear-link and subsurface buoy. The pear-link provided the attachment point for a strong downline and large buoy. The three eye pins helped distribute the load over a greater bottom area thus increasing the overall holding power of the system (Smith pers. com.). Often, however, only one of the eye pins took the strain of the vessel; consequently, the other two eye pins served as back-ups in case of a failure of one of the eye pins. The triad was eventually modified into a two eye pin system.

A similar system uses a heavy duty swaged cable, or multiple cables secured by cable clamps, connecting the two eye pins. The downline is attached by a sliding shackle to the cable so that both eye pins take the strain thereby increasing the holding power adequately for use by large live-aboard dive boats (Hassen pers. com.). Wayne Hassen also successfully modified a traditional welded 1.91 cm (3/4 in.) eye pin by bending 1.91 cm (3/4 in.) rod stock at each end so that it fit into a 10.16 cm (4 in.) cement-filled hole with no welding involved to accommodate his growing fleet of live-aboard dive boats.

In other areas, systems using two anchoring points have proved to be successful. In Hawaii, eye pins were doubled up with two short chains attaching the eye pins to the down-line and a subsurface buoy in order to provide a back up anchor point (Leicher pers. com.). In Cay Sal, Bahamas, Capt. Tom Guarino reported that his 27 meter converted crew boat withstood winds in excess of 50 kts in semi-protected waters while moored to a double eye pin system by a sliding shackle on a chain connecting two single 45.72 cm (18 in.) by 1.59 cm (5/8 in.) eye pins cemented into the bottom approximately 2 meters apart (Guarino pers. com.). Peter Hughes has successfully deployed a double galvanized 2.54 cm (1 in.) eye pin system with holes drilled about a meter apart at an angle to one another so that the combined pull on the eye pins opposes the direction of pull out (Hughes pers. com.). Cable and chain connecting double eye pins tend to become wear points and should be checked periodically for replacement needs.

A rigid triad was deployed in Saba, Netherlands Antilles in March, 1989 at the request of the Saba Marine Park manager to accommodate three large live-aboard dive boats that had begun operating there. Seven units were installed consisting of three approximately 0.6 meter lengths of heavy channel iron welded together on the same plane symmetrically with a pad eye in the center for the downline and 3.81 cm (1-1/2 in.) holes accommodating 0.76 m (2-1/2 ft.) long by 3.18 cm (1-1/4 in.) galvanized all-thread rods at the end of the channel iron arms. Three 5.08 cm (2 in.) by 60.96 cm (24 in.) holes were drilled into the bottom and the 3.18 cm (1-1/4 in.) all-thread rod was cemented into the holes and secured to the channel iron with double nuts. Some difficulties were experienced with positioning the rigid triad on level solid substrate for all the drill holes. Occasional loosening of the nuts occurred after a period of use.

At the same time the rigid triad was deployed, the two eye pin concept was modified to eliminate chain or cable and associated hardware by utilizing an inverted "U"-shaped anchor to provide increased holding power and eliminate the possibility of a welded eye failure. Two inverted "U" anchors were installed experimentally to accommodate large boats, one in Saba and one in the British Virgin Islands in March, 1989. The Saba inverted U was fabricated from a one piece, approximately 1.68 m (5-1/2 ft.) long by 1.91 cm (3/4-in.), 316 stainless steel all-thread rod by lathing the center 45.7 cm (18 in.) and bending it into a "U" with 60.96 cm (24-in.) long legs positioned 30.48 cm (12 in.) apart. Petit™ two-part epoxy paste was applied to the legs while out of the water and the unit taken into the water and inserted into 3.18 cm (1-1/4 in.) holes pre-drilled into volcanic basalt rock. Tapped into place with a hammer, the inverted "U" anchor formed a low profile ring without any welds. This provided a non-moveable attachment point for a single shackle and down-line (simplifying the downline attachment) while distributing the load over a greater substrate area. The BVI inverted "U" anchor was manufactured from 1.91 cm (3/4 in.) 316 stainless steel smooth stock bent into a "U" shape with 60.96 cm (24 in.) legs 30.48 cm (12 in.) apart and with 5.08 cm (2 in.) cross rods welded to the end of the legs. This unit was secured with Type II cement in 60.96 cm (24 in.) deep by 6.35 cm (2-1/2 in.) diameter holes providing the same profile and distribution of load as the Saba inverted "U" anchor (Fig. 2).

During this same general time period, inverted "U" anchors were also developed by Craig Quirolo of Reef Relief Foundation for "Big Boat Moorings" off Key West, Florida in response to the increase in large boat visitation in the lower Florida Keys. These were similar to the BVI inverted "U" except the legs were positioned 45.72 cm (18 in.) apart (Quirolo pers. com.). In May, 1990, twelve heavy duty inverted "U" anchors were installed on the Flower Gardens Bank in the Gulf of Mexico, 161 km off the coast of Texas by the Gulf Reef Environmental Action Team (GREAT). These were manufactured with heavy 2.54 cm (1 in.) 316 stainless steel stock with 60.96 cm (24 in.) long legs 30.48 cm (12 in.) apart with cross rods on the end of the legs and set with Portland Type II cement in 7.62 cm (3 in.) diameter holes. The 3.81 cm (1-1/2 in.) downline was connected to a large 76.2 cm (30 in.) buoy. This strong system was tested by a 30.48 m (100 ft.) crew boat (converted for diving) during thirty minutes of sustained 35 kt winds with gusts to 50 kts 161 km off shore. The system held without any sign of failure (Rinn pers. com.). The twelve-buoy system has now been incorporated into the Flower Gardens Bank National Marine Sanctuary program.

A four-point mooring system was deployed to get strong holding power in limestone substrate for anchoring the 30.48 m (100 ft.) by 15.24 m (50 ft.) Mobile Support Base (MSB) barge for the NOAA Aquarius underwater habitat off Key Largo, Florida. The bow moorings were placed 183 m out and the stern moorings placed 85.34 m out from the barge. Each mooring point consisted of a heavy-duty pad eye with approximately a one square meter footprint secured by four 3.175 cm (1-1/4 in.) by 1.22 m (4 ft.) all-thread stainless steel rods, drilled and cemented into the substrate and double-bolted to the pad eye. A high strength non-shrink 5 star marine grade grout was used to cement the eye pins. Sampson braid nylon line 5.08 cm (2 in.) in diameter was used as a downline from a large 132 cm (52-in.) diameter steel buoy. Another length of Sampson braid line connected the downline to the barge. The system withstood 45 kt sustained winds with gusts to 60 kts from tropical storm Gordon with seas building to 5.5 meters while saturation divers were brought out of saturation. This is a good example of how the original eye pin concept was expanded to greatly increase holding power in the same limestone substrate and serves as a model for increasing holding power for ship applications.

Soft bottom: Manta Ray™ mooring anchors

The original eye pin system was designed to protect coral reef environments, but as mooring projects moved into areas without hard limestone substrate, there was a need to secure mooring anchors in soft bottom areas consisting of sand, grass, or rubble. These were the locations traditionally served by weighted moorings with their concurrent problems (VanBreda 1992). Initial solutions were not entirely satisfactory. A 318 kg railroad wheel anchor moved with a 14.63 m (48 ft.) boat attached in 20 kt. winds, and a 1.68 m (5-1/2 ft.) #813 A. B. Chance™ screw anchor augured into the sand eventually worked up and out of the bottom (Halas 1985).

In the spring of 1990, a Manta Ray™ anchor, used to secure utility pole guy wires, was tested for underwater use in the Key Largo National Marine Sanctuary in the grass and sand areas of Grecian Rocks and Key Largo Dry Rocks. The original Manta Ray™ anchor tested consisted of the MR-1 flat anchor plate with a 2.13 cm (7 ft.) by 2.54 cm (1 in.) galvanized rod threaded at each end with a "triple-eye" nut at the top. Later, to adapt the land model Manta Ray™ anchor to the marine environment, a few modifications were introduced. Now, a large eye nut replaces the restrictive "triple eye" nut used for utility poles and easily accommodates several shackle sizes. Land models have three components threaded and screwed together but marine Manta Ray™ anchors (Fig.2) are welded into one piece units to prevent unscrewing of the system with the shifting orientation of the attached boat. Hot-dipped galvanizing after welding protects against corrosion. Minor changes were made to the installation equipment (load-locker, baseplate, and adaptor setting bar) to facilitate underwater installation.

The anchor inventory was increased by adding marine models with larger anchor plates for increased holding power. A variety of anchor sizes are now available for different bottom types. Probably the best for most mooring buoy applications, the MR-SRM weighing 19.3 kg (42.5 lbs.) provides a broad surface of 916.12 sq.cm (142 sq. in.) for greater holding power in soft substrates. For extremely soft bottom material such as mud, silt, or very loose sand, the "Muskeg," 36.3 kg, 2,593.5 sq.cm, (80 lbs., 402 sq.in.) has been designed to provide even greater surface area and weight to maintain holding power. The MR-1M, 15.2 kg, 458 sq.cm, (33.5 lbs., 71 sq. in.) is versatile and can provide a suitable, less expensive anchor for smaller vessels in protected waters. Smaller and narrower, the MR-2M anchors, 14.3 kg, 271 sq. cm, (31.5 lbs., 42 sq. in.) may penetrate more easily into rocky rubble areas and develop strong holding power. These and the MR-3M anchors provide good mooring anchors for demarcation buoys. All the marine Manta Ray™ anchors have a structural rating of 9,074 kg (20,000 lbs.). For the greatest holding power, it is best to use the largest anchor that can reasonably penetrate at least 2.13 m (7 ft.) into the substrate.

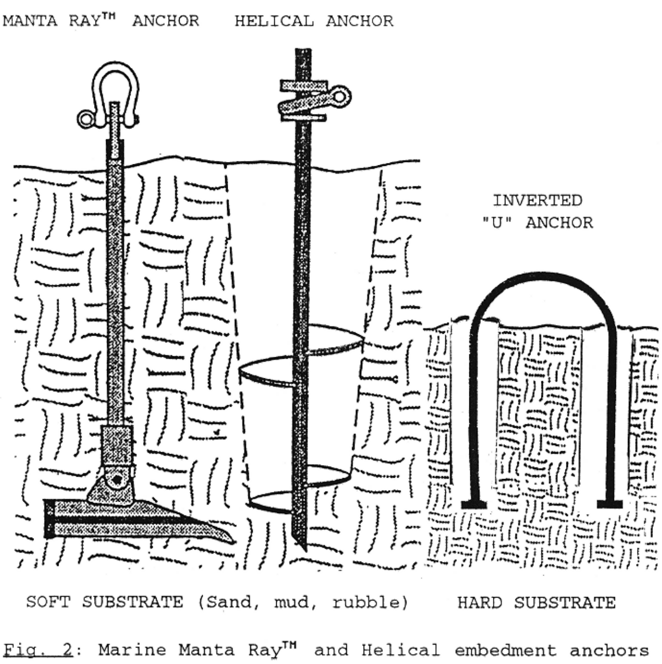

Fig. 2: Marine Manta Ray™ and Helical embedment anchors in soft substrate. Inverted "U" anchor in hard substrate. (Drawings not to scale.)

To install the marine Manta Ray™ anchor systems underwater, a diver drives the Manta Ray™ anchor into the substrate using a Stanley™ BR-67 underwater jackhammer and drive steel gad set. After attaching an adaptor setting bar to the eye nut, the 2.13 m (7 ft.) rod is driven below the substrate and a two-piece base plate positioned over the protruding bar. Handlers on the surface, exchange the BR-67 jackhammer for the load-locker hydraulic tool which, when in place on the base plates on the bottom, grips the adaptor setting bar in order to pull up and set the anchor plate. A pressure gauge on the load-locker measures the force exerted in pulling up and setting the anchor and provides holding power rating for the system. When the eye of the rod protrudes above the substrate, the load-locker is disengaged and a 45.4 kg (100-lb.) lift bag is used to return it to the surface. Other heavy installation pieces are also retrieved with lift bags.

Although its optimum use is in hard-packed sand, the Manta Ray™ system provides secure holding power for moorings in loose sand, rubble, and grassy sea beds where the railroad wheel and 1.68 m (5-1/2 ft.) screw anchor had proved inadequate. The Manta Ray™ will also drive past or through rocks, shells, and small buried coral heads successfully and loads often reach more than 7,713 kg (17,000 lbs.) of force. Immediately after installation, a mooring buoy array can be attached and used.

Soft bottom: Multiple Manta Ray™ anchors
For stronger moorings in soft substrates, boats over 17 m long, sea conditions over 1.5 m waves, and for long term attachment to the mooring system, multiple Manta Ray™ anchors have been successfully used. To satisfy these conditions and provide redundancy, the National Park Service in St. John, U. S. Virgin Islands successfully installed triple Manta Ray™ anchors for a single mooring similar to the Cayman Island triad anchor eye pin system (Kelley pers. com.). Double Manta Ray™ anchors, either using a chain-connected triangular metal "fish plate" or a sliding shackle over a connecting chain, have also been used successfully to provide increased holding power. The sliding shackle or "fish plate" in tension serves to distribute the load between the two Manta Ray™ anchors. The system causes little disturbance when used with a sub-surface buoy which holds the chain off the bottom. Use of multiple Muskeg Manta Ray™ anchors could increase holding power to accommodate even larger vessels.

Soft bottom: Helical anchors
Helical plate or "screw" anchors were invented in the early 1900's. Helical anchors (Fig. 2) used in the marine environment are generally for heavy-duty long term anchoring or "hurricane" applications in substrate containing deep soft sediments. They can be installed with a hydraulic system mounted on a stationary vessel or by a diver using a slow turning high-torque hydraulic power head. The current designs use either hollow or solid square stock iron shafts that can be lengthened by adding extensions to reach a desired torque reading in deep loose substrate. Very strong holding values can be obtained when these systems are deployed with extensions deep into the substrate. The systems perform well in resisting side loads and have the capability of being removed if necessary. "Teeth" added to the leading edge of the helical plate provides some cutting capability in hard substrates when bored in with downward pressure from a stationary vessel. A floating line or a line with a sub-surface buoy will prevent terminal tackle contact with the bottom.

Mooring installation equipment
The basic hydraulic installation system for embedment anchor systems (Halas 1984) accounts for the majority of mooring installations. The flow of hydraulic fluid from a power source through hoses to and from a tool is an efficient means of installing embedment anchors in a variety of conditions. Hydraulic systems provide continuous power to drive underwater tools and are reliable over time.
The power source can be either from a power take-off (PTO) attached to the main propulsion engine of the support boat or from a portable power unit. Advancements in portable power units incorporate light-weight twin cylinder gas engines mounted on light, rust-free aluminum frames using "power on demand" throttle linkage. The result is a savings in weight and an increase in efficiency and reliability.

Plastic hydraulic hose using non-conductive reinforcement is advantageous for underwater use. The neutral to slightly negative hose, compared to a heavy wire reinforced hose, minimizes contact with the bottom. Stainless steel ends and quick disconnect fittings provide good long lasting corrosion-free connections. A small, but powerful, Stanley™ DL-09 hand-held drill with a trigger guard and cross handle serves as a strong reliable light weight drill. Using two different adaptors, core barrels with 3.18 cm (1-1/4 in.) by 7 hub can be used as well as smaller diameter drill bits with a 1.59 cm (5/8 in.) by 11 hub. Core barrels using surface set or impregnated diamonds are used by geologists taking core samples and in mooring eye pin installations. Thick-walled core barrels using carbide teeth provide a faster, more aggressive cut in limestone. In hard volcanic rock, hammer drills or sinker drills using fluted drill bits or drill steel are needed to effectively and efficiently penetrate the substrate with 1.91 cm (3/4 in.) to 2.22 cm (7/8 in.) holes. The Stanley™ HD-45 is an effective tool for this, requiring no additional flushing with water or air. In these smaller holes, good holding power can be obtained with underwater adhesive epoxy.

For Manta Ray™ applications, the BR-67 jackhammer is effective in most situations encountered. In the Exuma Cays, Bahamas, Ray Darville has effectively used a portable water pump to work MR-SRM Manta Ray™ anchors into 2.4 m of consistent sand, free of major obstructions, and set the Manta plate (Darville, pers. com.). Large Muskeg anchors on chain have also been deployed in the harbor at Highbourne Key, Exumas by water jet in soft consistent sand bottom (Doyle pers. com.).

For helical anchor installations originally accomplished from a stationary vessel in shallow water, a slow turning high-torque hydraulic motor has been developed to enable diver-operated installations in deeper water. A long resistant leverage arm or anchor is required to resist the back force created during installation. The use of air powered drills is generally considered less effective than hydraulically driven drills. If a large compressor and air bank is available, however, an air drill can be considered for small installation projects. A heavy duty model air drill can effectively drill a 55.88 cm (22 in.) by 5.08 cm (2 in.) diameter hole in limestone using approximately four 2.25 cubic meter (80 cubic ft.) SCUBA tanks of air (Doyle pers. com.).

RESULTS

Pull tests (Table 2) conducted on topside wet Key Largo cap rock using both epoxy adhesive and Portland Type II cement produced very high pull out rates in most cases. The extreme force distorted anchor eyes and compromised welds before failure. These values were greater than the load limits of commonly used lines and shackles and therefore would not have been reached in an actual mooring situ-ation. Eye distortion began to occur at approximately 7,258 kg (16,000 lbs.) and continued until weld failure occurred at approximately 9,072 kg (20,000 lbs.). Higher rates were achieved when the weld site was lengthened along the eye pin shank. In some cases, voids in the substrate contributed to ground failure before eye pin distortion occurred.

The first attempt at testing the pull out strength of the inverted "U" anchor embedded in cement resulted in the pulling apparatus breaking at 17,164 kg (37,840 lbs.). During a second attempt with a new stronger device, an extremely high value (28,836 kg or 63,572 lbs.) was attained before the cross rod weld on one leg failed at the bottom of the hole. The force suddenly dropped to 15,876 kg (35,000 lbs.) but the inverted "U" anchor continued to hold and did not pull out although the stainless steel stretched from a "U"-shape to a "V".

Tests were conducted underwater with single stainless steel anchor eye pins and underwater adhesive epoxy on

Table 2: Results of tension tests on mooring anchors embedded in cement and underwater adhesive epoxy and mooring system materials pulled to failure. An asterisk after sample number indicates underwater tests and ++UC indicates probable upward compression of the substrate.

TENSION PULL-OUT TESTING
MOORING ANCHOR EYE PINS (45.72 cm long)
IN LIMESTONE SUBSTRATE
(TESTING TO FAILURE)
SEPTEMBER, 1994

SAMPLE NO.	APPLIED LOAD (kg)/(lbs.)	MATERIALS	FAILURE MODE / NOTES
CEMENT MATRIX:			
#1	9,208 kg 20,300 lbs.	1.59 cm 316 StSt pin with foot. 5.08 cm hole.	Eye weld failed, Pulling vehicle broke.
#2	8,256 kg 18,200 lbs.	1.59 cm 316 StSt threaded pin, 1.91 cm hole.	Substrate failed, Steel eye began to distort at 4082 kg
#3	9,208 kg 20,300 lbs.	1.59 cm 316 StSt part. thread 1.91 cm hole.	Eye weld gave, pin continued to hold.
#4	17,164 kg 37,840 lbs.	"U" anchor, 316 StSt 1.91 cm pin w/foot, Two 5.08 cm holes.	Stretched to "V", no pull-out, cracked ground, broke test device.
UNDERWATER ADHESIVE EPOXY MATRIX:			
#5*	5,955 kg 13,129 lbs.	1.59 cm 316 StSt threaded pin	Bottom failed with 12.7 cm cone. UC.**
#6*	5,799 kg 12,784 lbs.	1.59 cm 316 StSt threaded pin	Bottom failed with 27.94 cm cone. UC.**
#7*	7,209 kg 15,893 lbs.	1.91 cm 316 StSt threaded pin	Bottom failed, 7.6 cm cone, bent anchor.
#8*	4,388 kg 9,674 lbs.	1.91 cm 316 StSt threaded pin	Bottom failed, 7.6 cm cone, UC.**
#9*	8,149 kg 17,966 lbs.	1.91 cm 316 StSt threaded pin	Bond failed, UC.**
#10*	4,077 kg & 5,955 kg 8,987 lbs.& 13,129 lbs.	1.59 cm 316 StSt threaded pin	Bond failed, two-way bend. Failed and then held to 5,955 kg.
#11	11,597 kg 25,567 lbs.	1.91 cm 316 StSt threaded pin	Bottom failed, UC.**
#12	28,836 kg 63,572 lbs.	"U" anchor, 2 legs, 1.91x61 cm. 316 StSt	Weld failed on one leg, 5-resets req.to extend test, no pull-out.Held at 15,876 kg
#13	7,209 kg 15,893 lbs.	5/8-in. 316 StSt Knurled	Bottom failed.
#14	11,911 kg 26,258 lbs.	5/8-in. 316 StSt No threads.	Steel failure.
SYSTEM MATERIALS TEST:			
#15	4,702 kg 10,365 lbs.	1.03 cm Wichard 316 StSt shackle	Cross pin failed at thread.
#16	6,426 kg 14,166 lbs.	1.19 cm Wichard 316 StSt shackle	Cross pin failed at thread.
#17	9,403 kg 20,730 lbs.	1.27 cm Taiwan 316 StSt shackle	Cross pin failed at thread.
#18	2,508 kg 5,528 lbs.	1.91 cm Polypropylene line.	1 of 3 braids failed

near shore limestone hard bottom. The bottom tested appeared to be somewhat more porous than the topside Key Largo cap rock. Values attained were slightly lower than surface tests but still reached strengths from 4,396 kg (9,674 lbs.) to 8,149 kg (17,966 lbs.) before the anchor eye pins began moving up through the substrate (Table 2).

DISCUSSION

The need to develop strong mooring systems in a wide variety of bottom types has led to the advancement of mooring technology by combining the original embedment anchor concept with additional modifications, tools, and methods. To meet the problems posed by varying substrates, embedded anchors effective for those situations have been developed. A suite of tools enabling efficient installation has been a key element in the implementation of moorings in the diverse conditions encountered in the world's reef systems. Embedment anchors and mooring systems are now used globally to protect tropical coral reefs and the list of locations where they are found continues to expand (Table 1).

Advancements in mooring technology have broadened the scope of embedded anchors, but mooring buoy site selection remains an important element in establishing a strong permanent mooring attachment point. Where there is a solid limestone base, the site selection process can be uncomplicated but becomes more complex with other bottom substrates. Increased boat size and the need to tolerate stronger sea conditions in narrowly defined sites can add to that difficulty. Although increasing the area for site selection will improve the chances of establishing a stronger mooring attachment point, a mooring installation should not be forced into an unsuitable substrate that may not have sufficient holding power.

Some challenges remain. Steep slopes composed of widespread living coral colonies growing over loose deep rubble, like that found on Bonaire's reefs, pose problems for secure non-damaging mooring anchors. Walls or steep drop-off areas, especially those situated in shallow waters such as found in Palau, make embedded anchor placement difficult. Great tidal ranges require adaptive systems. Strong currents impede installation techniques. A bottom consisting of sand at a depth of one to two meters over hard substrate is particularly difficult for establishing a secure mooring. A means of overcoming human frailty by providing a theft-proof system without heavy duty hardware remains a challenge in some localities.

ACKNOWLEDGMENTS

I would like to express my gratitude to all the people I have worked with in the United States and overseas during mooring buoy installation projects that have added to the body of knowledge on mooring anchor system technology. Harold Hudson, who provided the original inspiration for the embedment eye pin system, has continued to be supportive as new techniques have been introduced. Jeff Fisher and the team at Foresight Products L.L.C. have assisted me greatly since the introduction of the Manta Ray™ anchors by working to adapt the anchors and equipment for use underwater. I appreciate the time and energy expended by Norman Schmotzer of B & A Manufacturing Co., Steve Koltenbeck and Bert Mayer of Gunnebo Fastening Co., and Wayne Ray, representing Stanley™ Tools and Hydraulic Supply Company, to help quantify the strength of the cement and epoxy embedment eye pin systems resulting in an additional eye pin installation technique. I owe special thanks to my wife, Judith F. Halas, for all her help.

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